A Workload for Evaluating Deep Packet Inspection Architectures

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Context

- Pattern matching over *large* data-sets of *complex* regular expressions

- Application:
  - Networking: deep packet inspection
    - *Network Intrusion Detection and Prevention Systems*
    - Content based routing
    - Content based billing
    - Application level filtering
  - Others:
    - Bibliographic search

- Architecture:
  - Memory centric architectures (using cache)

In this paper

- Workload to evaluate memory-centric regular expression matching architectures
  - » Synthetic rule-set generator
  - » Traffic generator
  - » Memory layout generator for NFA/DFA based designs

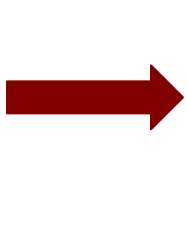
- Goal
  - » Fair comparison between designs
  - » Comprehensive tool

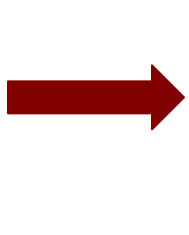
Background: handling multiple regex

Input text: ***…abcayxwknxKNZamkml…***

Search patterns

- **$regex_1$**
- **$regex_2$**
- **…**
- **$regex_N$**





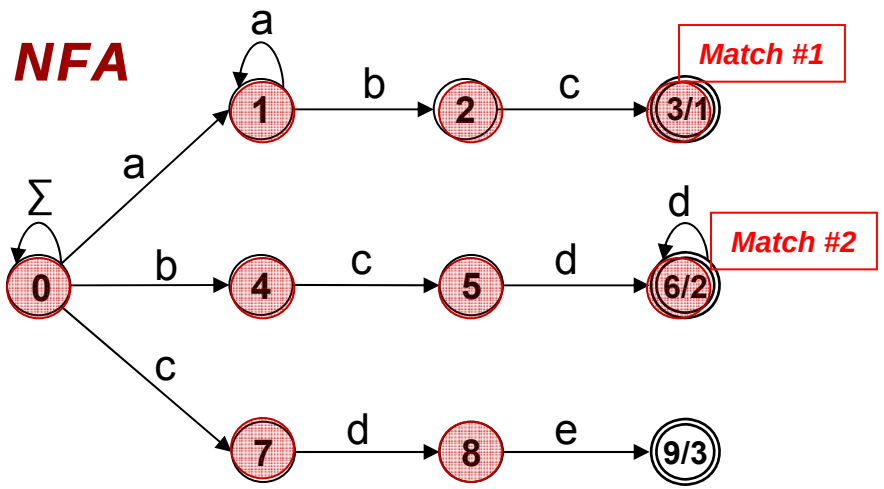
Linear processing time *independent of number of patterns*

FPGA designs

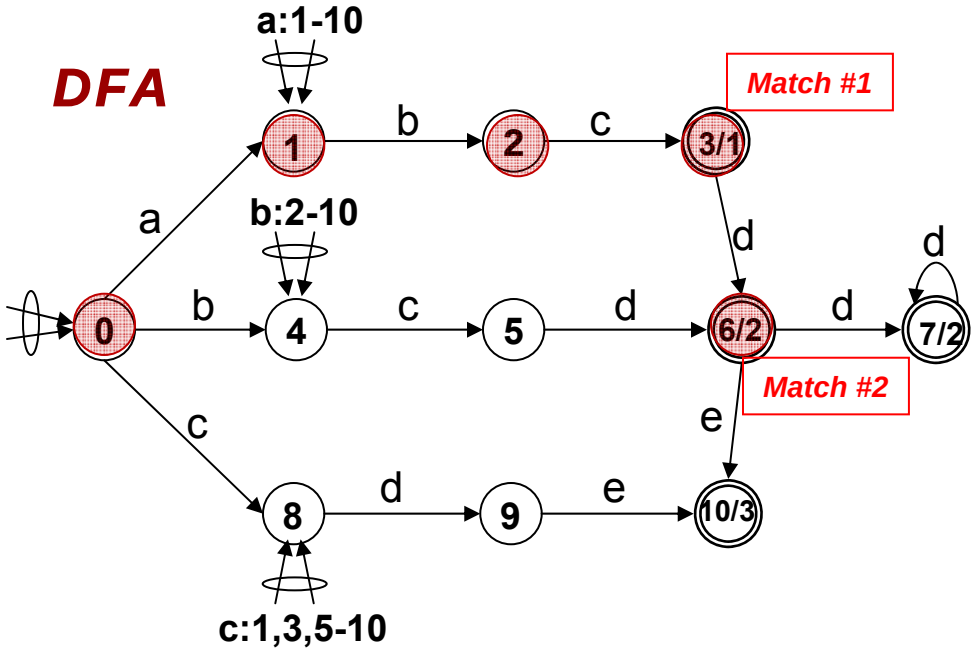
Memory-centric architectures

Background: Finite Automata

RegEx: (1) a^+bc (2) bcd^+ (3) cde



Text: *a b c d*



MEMORY BANDWIDTH:
# of state traversals per input character

Better for DFAs

MEMORY SIZE:
 # states and transitions

Better for NFAs

Regular Expression Taxonomy

- **Exact-match strings**
  - *Fixed size* patterns
  - Properties:
    1. DFA size ≤ NFA size ≤ # chars in the pattern-set
    2. Multiple transitions to a state are on the same char
    3. Optimizations based on hashing schemes possible

    - [A. Aho and M. Corasick, CACM 1975]
    - [S. Dharmapurikar et al, ANCS 2005]
    - [N. Artan et al, INFOCOM 2007]
    - [Kumar et al, ICNP 2007]

  - Not expressive enough:

    - [R. Sommer and V. Paxson, CCS 2003]
    - [J. Newsome et al, Security and Privacy Symposium 2005]
    - [Y. Xie et al, SIGCOMM 2008]

Regular Expression Taxonomy (cont'd)

- **Character sets, single wildcards**
  - » $[c_i\text{-}c_jc_k]$
  - » Properties:
    - Aho-Corasick and hashing schemes not directly applicable
    - *Exhaustive enumeration* of exact-match strings possible

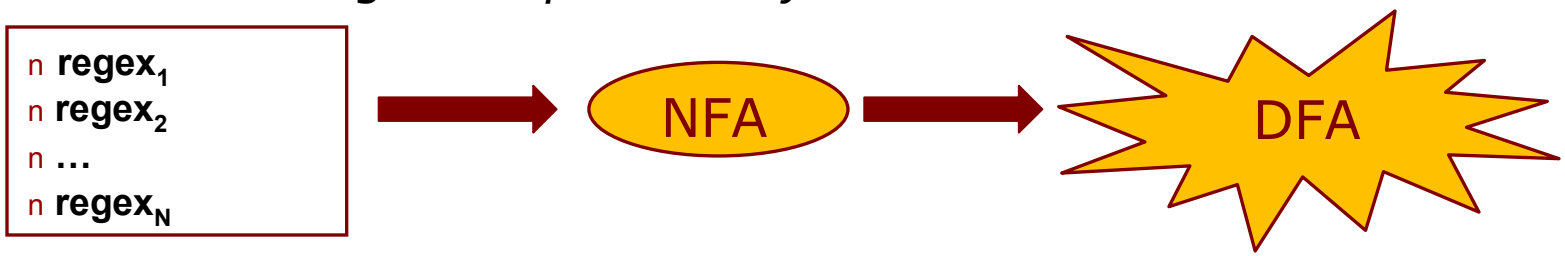
- **Simple character repetitions**
  - » c^+, c^*
  - » Properties:
    - DFA size ~ # chars in the pattern-set
    - Exhaustive enumeration of exact-match strings not possible

  ➡ hashing schemes not applicable

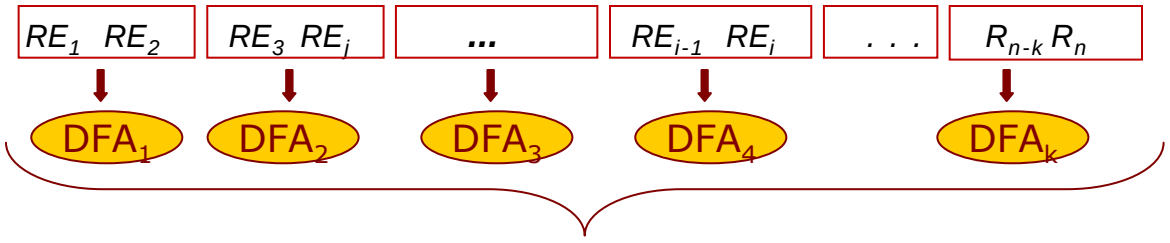
expressiveness

Regular Expression Taxonomy (cont'd)

- **Character sets and wildcards repetitions**
  - » .*, [^c_i-c_j]*
  - » Properties:
    - – As for simple char repetitions
    - – When compiling multiple regular expressions in the same DFA, DFA size can grow *exponentially*



  - – Viable solutions:
    - NFA
    - Rule partitioning into *multiple DFAs*



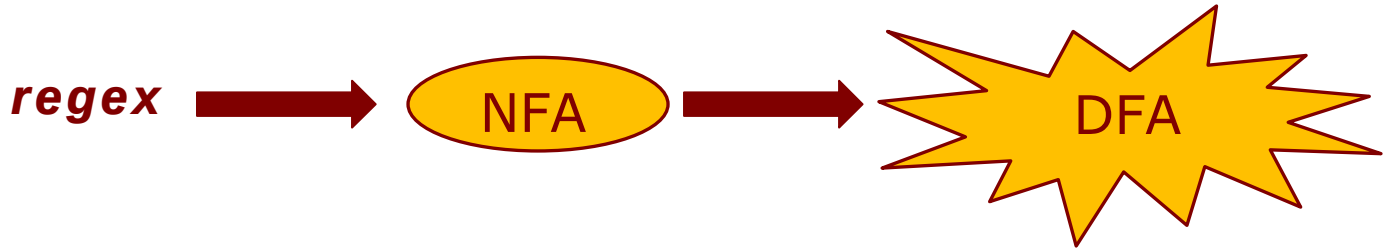
k concurrent DFAs □ *k* memory accesses/input char

expressiveness

Regular Expression Taxonomy (cont'd)

- **Counting constraints**
  - » *c*{m,n}, *sub-pattern*{m,n}
  - » .{m,n}, *[^c_i-c_j]*{m,n}

  - » Properties:
    - – Exhaustive enumeration not feasible for large character ranges and large *m*,*n*
    - – *Exponential* DFA size even on single regular expressions



    - – Viable solutions:
      - NFA
      - Hybrid-schemes using counters

expressiveness

In practice …

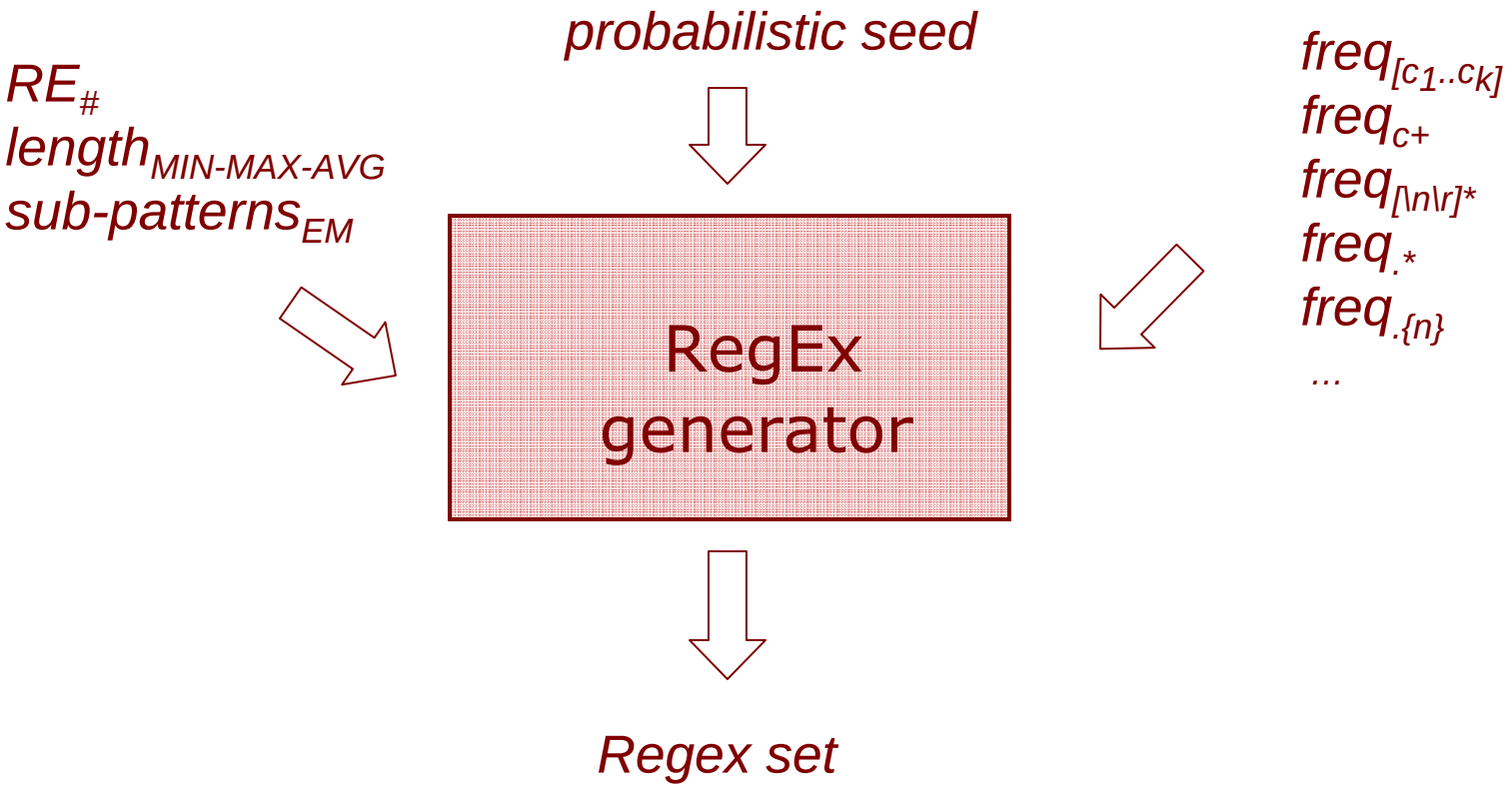
- **As of November 2007**

Data-set	# RegEx	$[c_1..c_n]$	.	c+	*string*+	$[c_1..c_n]$*	[^\n\r]*	.*	c{n}	*string*{n}	$[c_1..c_n]${n}	.{n}
Snort1	22	7	4	0	4	23	8	2	0	5	0	1
Snort2	78	3	1	0	0	202	81	18	2	0	1	0
Snort3	102	16	2	2	1	268	26	5	1	2	1	0
Snort4	468	9	14	3	7	113	468	38	0	7	11	3
Bro0.8	226	1399	0	0	0	0	0	10	0	8	0	0
Bro0.9	40	22	20	0	6	1	0	0	0	10	0	0
ClamAV	30411	0	0	0	0	0	0	1221	0	0	0	113

- **Over time**
  - » Data-set size
  - » Regular expression length
  - » Number of (repeated) character ranges
  - » Number of *dot-star*, *[^\n\r]** terms

  are increasing!

Synthetic regex generation

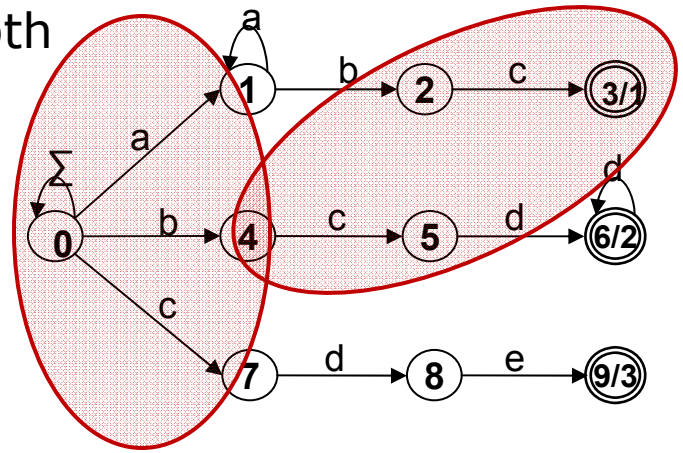


- RegEx: alternation of *exact-* and *non-exact match sub-patterns*, according to frequency parameters

Traffic model

- Goal:
  - » Generate synthetic traffic traces, rule-set dependent
  - » Simulate different degrees of malicious activity

- Observation:
  - » *Average/good* traffic:
    - limited to few low-depth states
    - high degree of *locality* (→ *fast path*)
  - » *Bad* traffic*:*
    - partial matches → move to higher depth
    - low degree of *locality* (→ *slow path*)
      - non-repetitive input streams
      - ideally random walks in FA



Traffic model (cont'd)

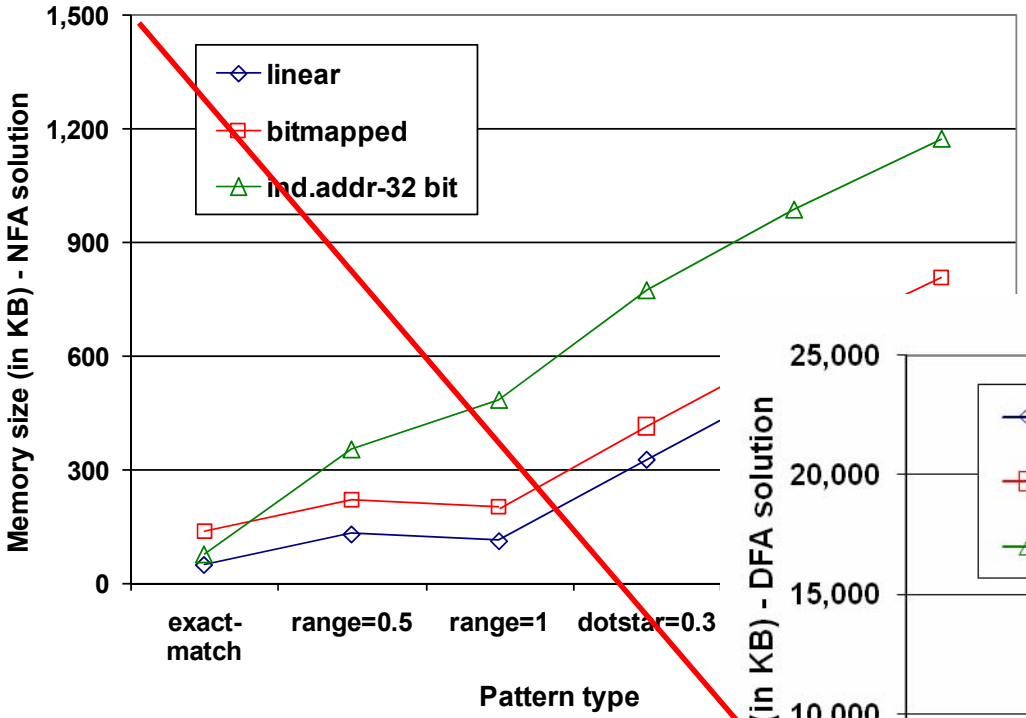
- Idea:
  - p_M: probability of malicious traffic
  - FA based model: *given p_M and set of active states, what is the next character in the input stream?*
- Operation:
  - *At each step:*
    1. *Forward transition w/ p_M*
    2. *Random char w/ (1- p_M)*
  - *In case (1)*
    - ***If** outgoing transitions exist*
      - *Depth/active set size driven selection*
    - ***else***
      - *Random char selection*

Memory encoding schemes

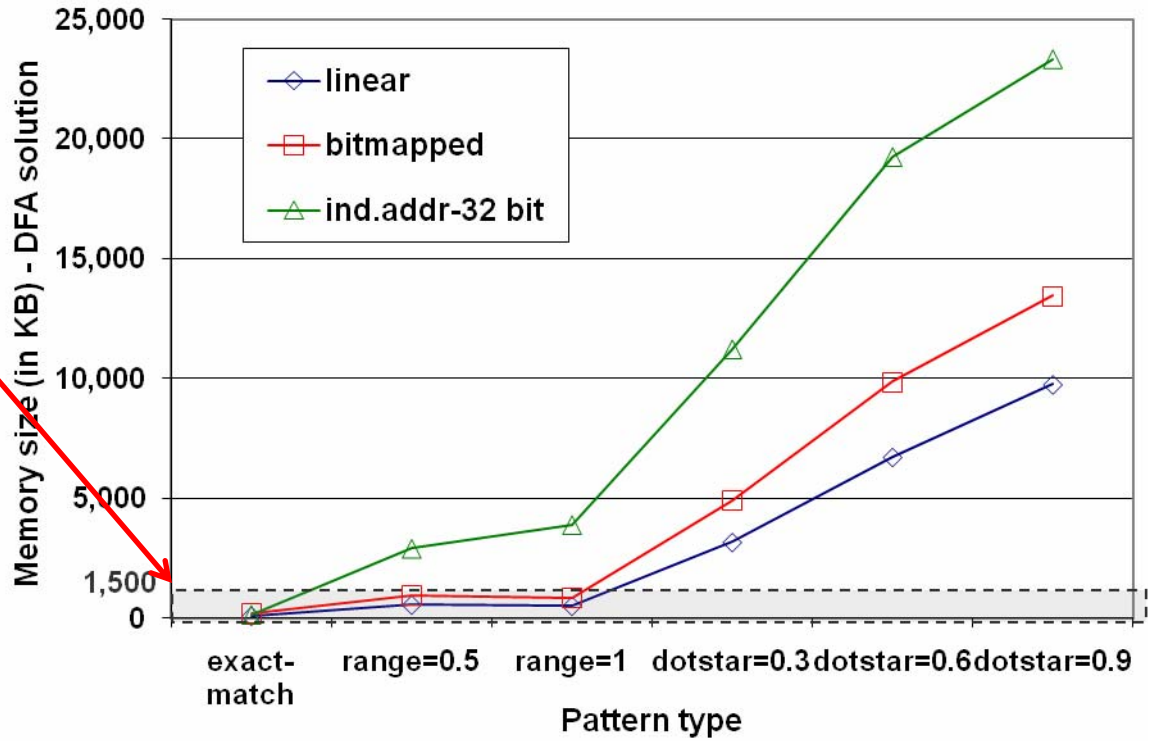
- Note:
  - NFA:
    - common prefixes collapsed
    - at most one epsilon tx/state
  - DFA:
    - default transition compression
      - [Kumar et al, SIGCOMM 2006]
      - [Becchi and Crowley, ANCS 2007]
        - At most *2N* state traversal to process text of length *N*

- Encoding schemes
  - *Linear, bitmapped, indirect addressing*
  - Affects
    - Memory footprint
    - Cost of state traversal

Memory footprint



NFA



DFA

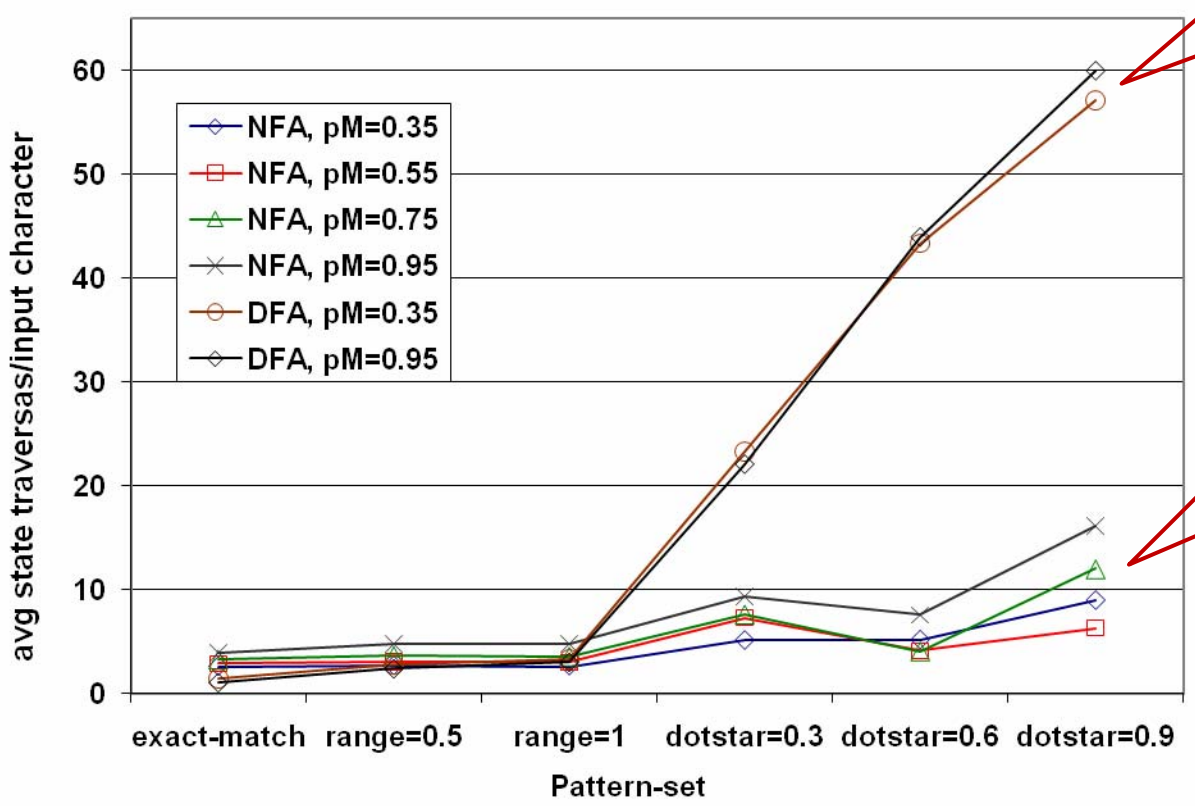
 # DFAs: 1 – 2 – 2 – 14 – 24 - 32

Experiments

	Parameter	Values
Traffic	p_M	0.35, 0.55, 0.75, 0.95
Cache	*size*	4 KB, 16KB, 64KB, 256KB
	line	64B
	associativity	DM
	hit latency	1 clock cycle
	miss latency	30 clock cycles
Memory layout	*encoding*	linear, bitmapped, ind. addr 32-bit ind. addr. 64-bit

State traversals/input char

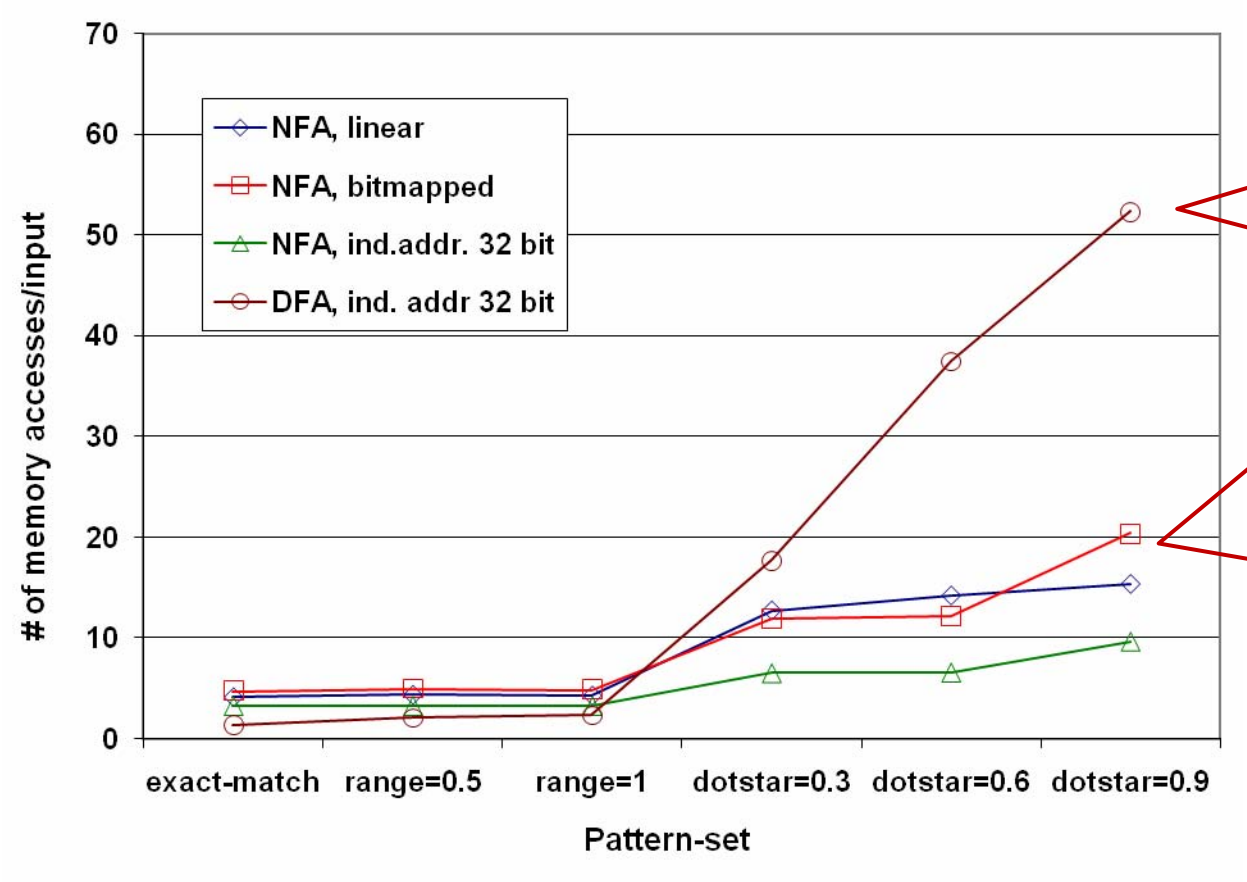
 # DFAs: 1 – 2 – 2 – 14 – 24 - 32



DFA
Rule-set clustering

NFA
p_M affects active set size

Effect of state encoding

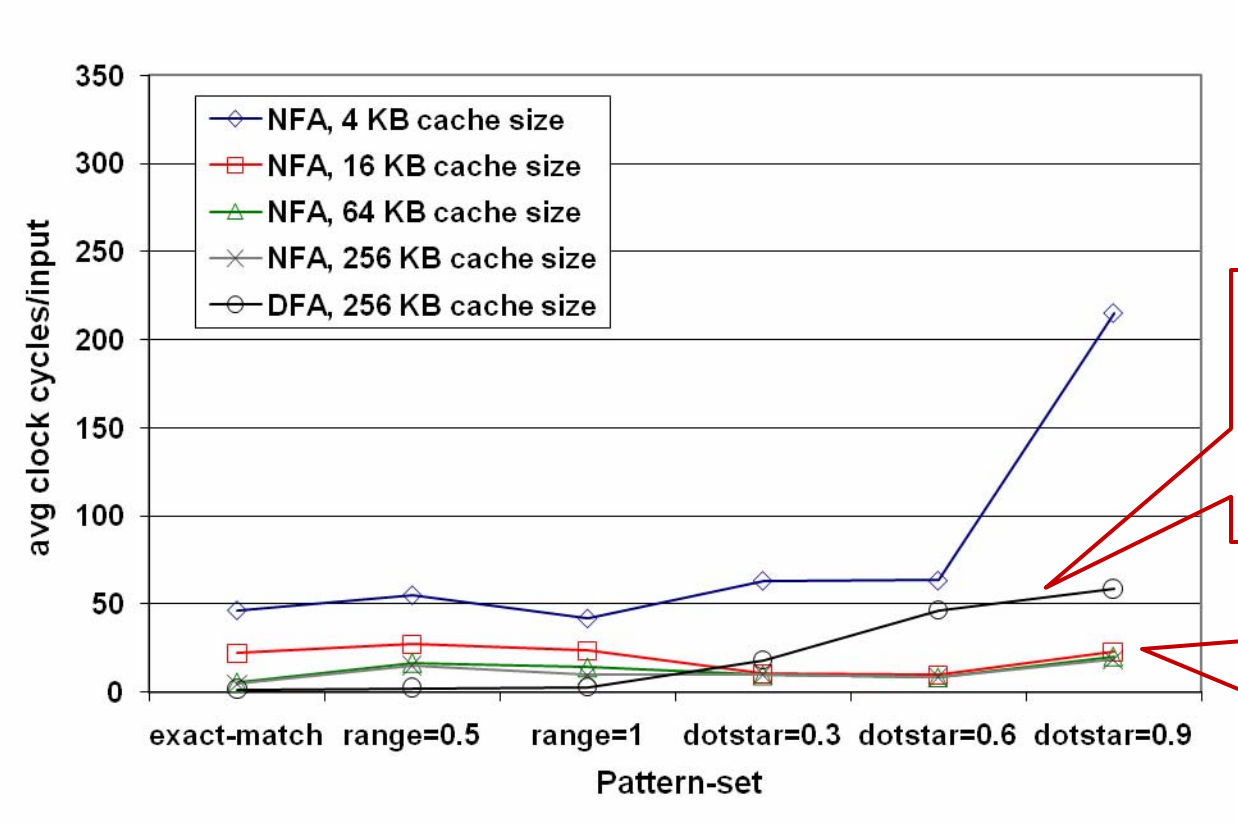


DFA
rule-partitioning
limiting factor

NFA
- indirect addressing preferable
- bitmap overhead not justified

$p_M = 0.35$

Effect of cache size



DFA
on complex rule-set
worse than NFA
even w/ 256KB

NFA
16KB cache
sufficient

Indirect addressing, p_M=0.95

Summary

- Proposal of workload to evaluate (memory-centric) regular expression matching architectures
  - » Synthetic regular expression generator
  - » Traffic trace generator
  - » Memory layout generator
  - » Cache simulator
- Model highlights:
  - » Performance depends on
    - – Rule-set size and complexity
    - – NFA/DFA representation
    - – Memory
    - – Cache size
- On complex rule-sets, NFA can outperform DFAs

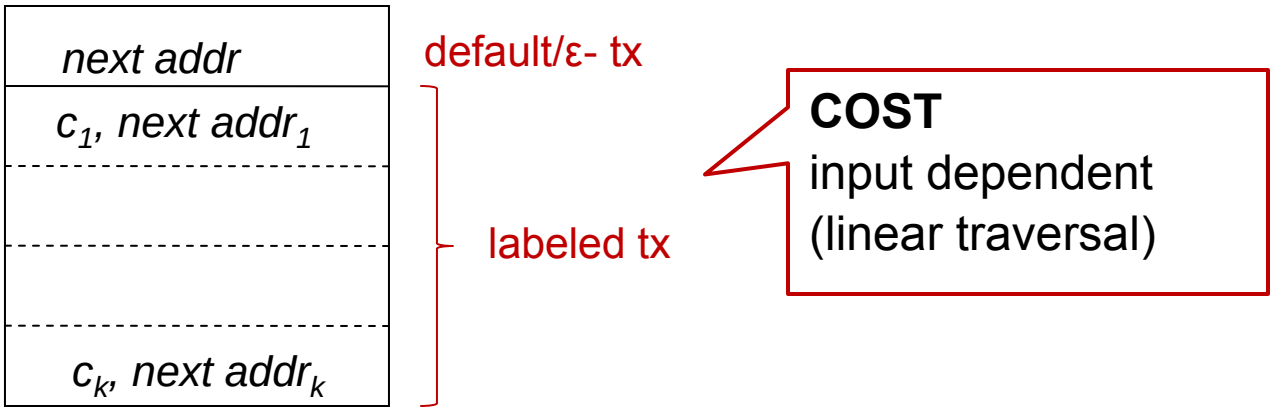
Thanks!

Questions?

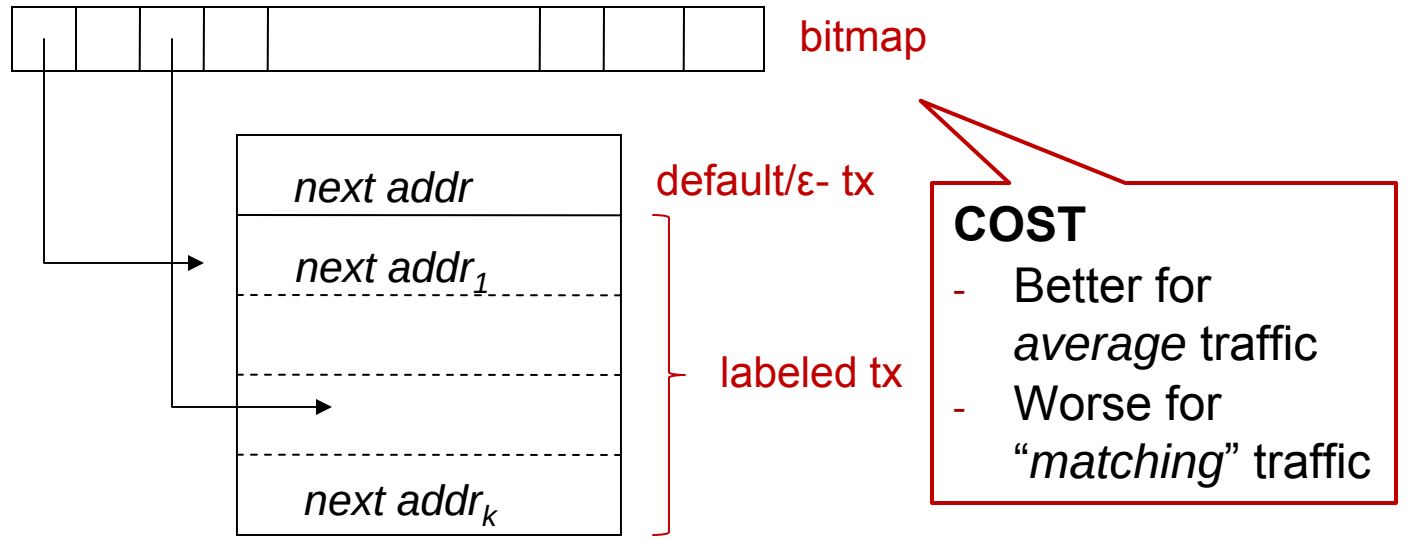
REGEX tool download: *http://regex.wustl.edu*

Memory encoding scheme (cont'd)

- Linear:

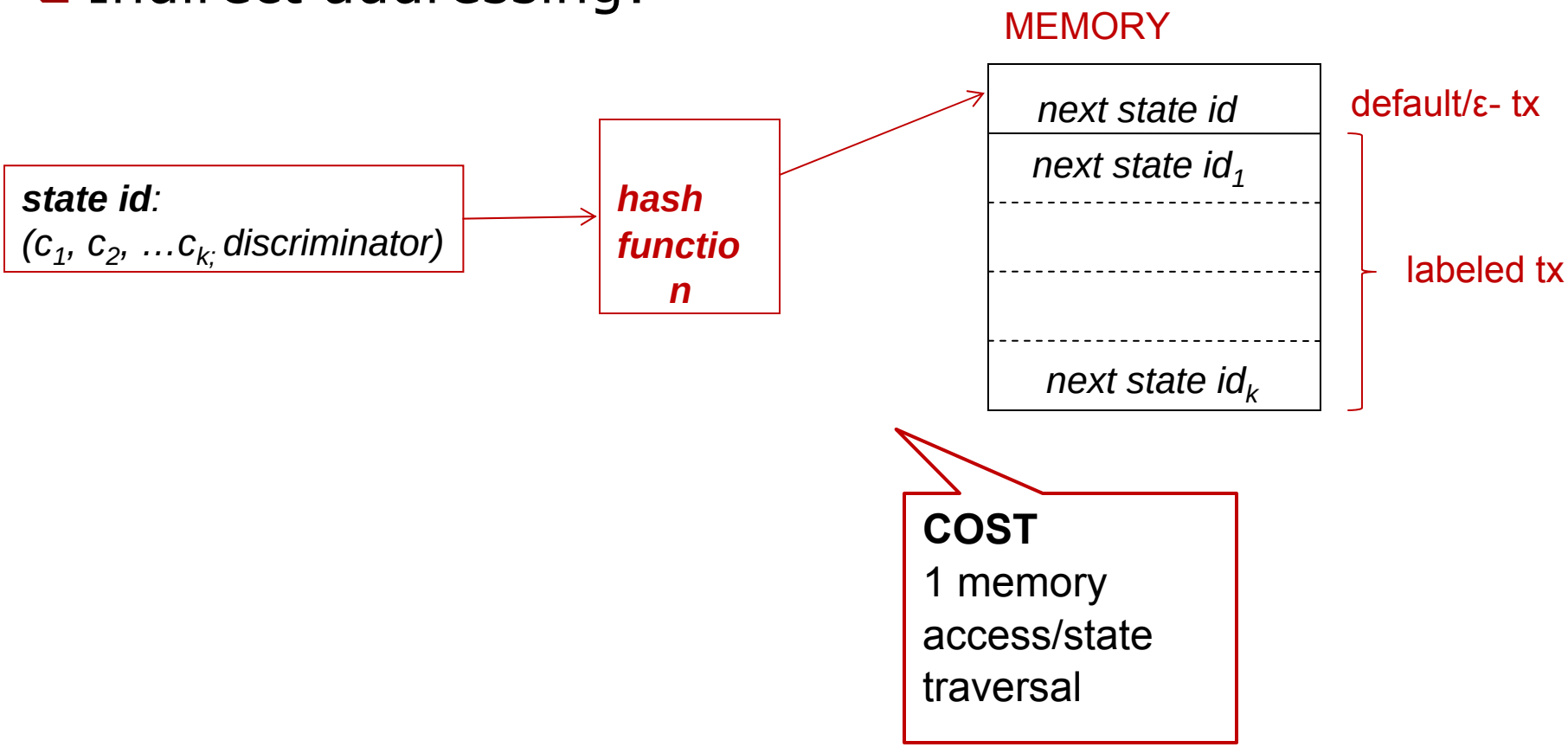


- Bitmapped:

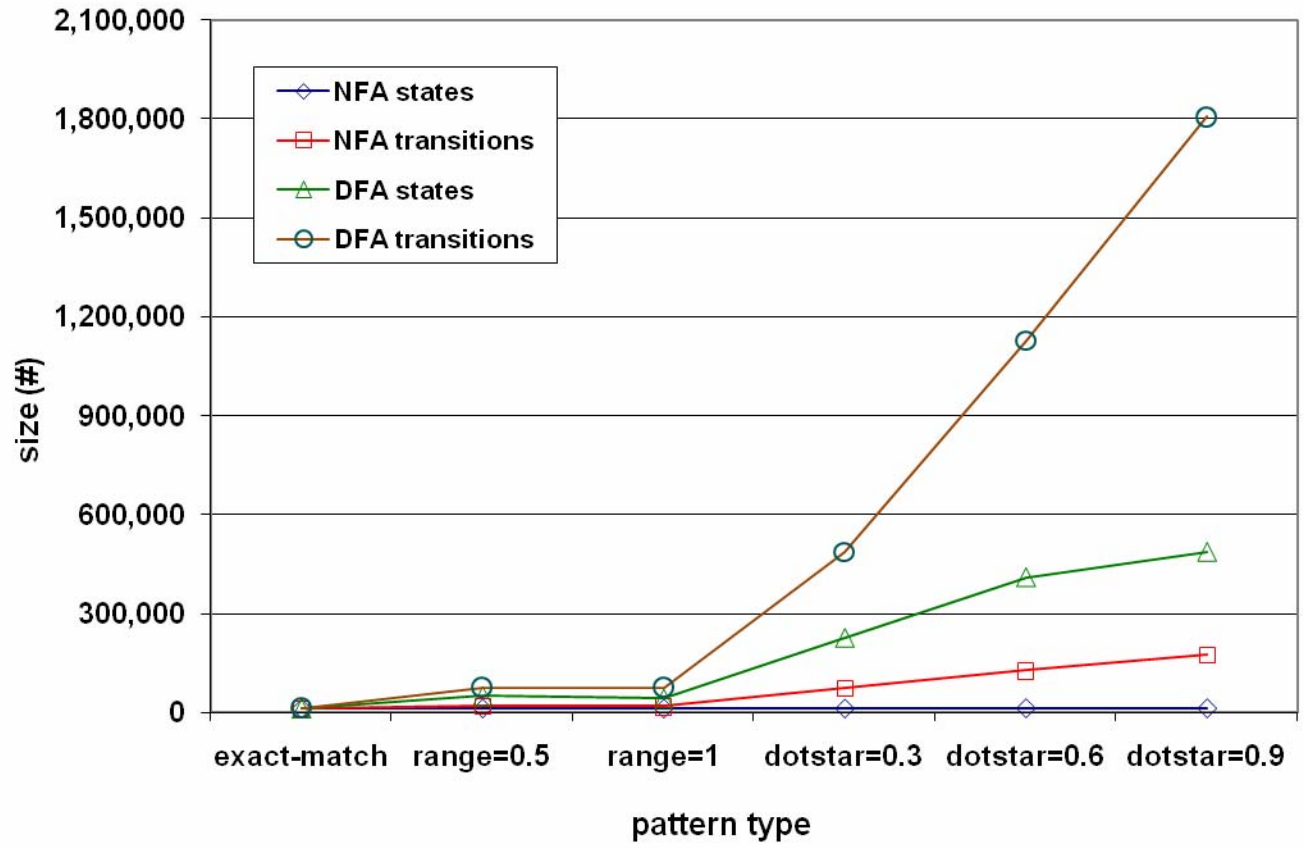


Memory encoding scheme (cont'd)

- Indirect addressing:



Automata size



 # DFAs: 1 – 2 – 2 – 14 – 24 - 32